VISUAL REPRESENTATION ALIGNMENT FOR MULTIMODAL LARGE LANGUAGE MODELS

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https://cvlab-kaist.github.io/VIRAL

ABSTRACT

Multimodal large language models (MLLMs) trained with visual instruction tuning have achieved strong performance across diverse tasks, yet they remain limited in vision-centric tasks such as object counting and spatial reasoning. We find that this limitation arises not merely from the choice of vision encoder, but from the lack of explicit supervision on visual representations during training, which causes detailed visual information to be gradually weakened even when strong vision foundation models (VFMs) are used as vision encoders. To this end, we present **VIsual Representation ALignment (VIRAL)**, a simple yet effective regularization strategy that aligns the internal visual representations of MLLMs with those of pre-trained VFMs. By explicitly enforcing this alignment, VIRAL preserves rich visual information within the MLLM while enabling it to leverage complementary visual knowledge from VFMs, thereby enhancing its ability to reason over complex visual inputs.

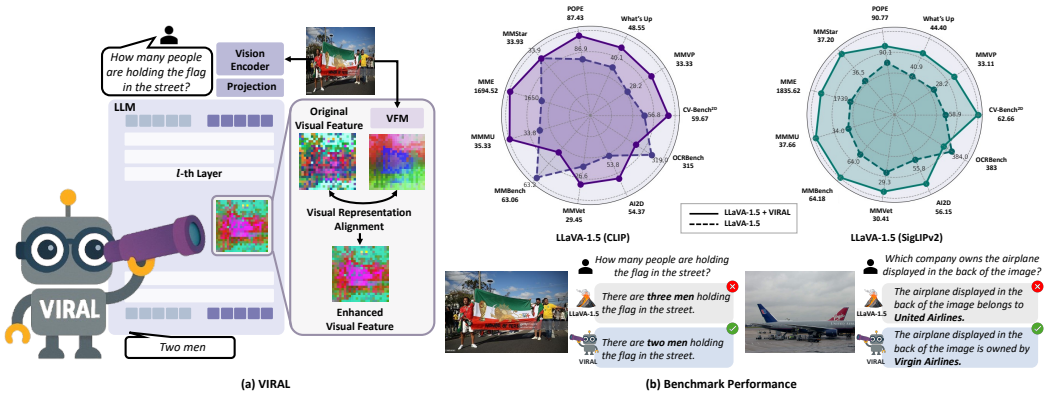

Figure 1: (a) **VIsual Representation ALignment (VIRAL)** introduces an auxiliary regularization objective on the visual pathway, preventing MLLMs from discarding detailed attributes of the input vision encoder during training while incorporating additional visual knowledge from vision foundation models (VFMs). (b) When trained with DINOv2 (Oquab et al., 2023) as the VFM, VIRAL consistently yields more accurate visually grounded responses and achieves substantial improvements over standard baselines (Liu et al., 2023) across diverse vision encoders, including CLIP (Radford et al., 2021) and SigLIPv2 (Tschannen et al., 2025).

1 INTRODUCTION

Recent advancements in multimodal large language models (MLLMs) OpenAI (2023); Bai et al. (2023a); Team et al. (2023); Chen et al. (2024c), particularly those employing visual instruction tuning Liu et al. (2023), have achieved notable success in diverse multimodal tasks. By connecting pretrained large language models (LLMs) Touvron et al. (2023); Chiang et al. (2023); Chen et al.

(2024c); Bai et al. (2025) with vision encoders Radford et al. (2021); Chen et al. (2024c); Tong et al. (2024a) through a lightweight vision–language projector, visual instruction tuning enables LLMs to effectively interpret and reason over visual inputs.

Despite these successes, numerous studies report persistent limitations in vision-centric tasks such as object counting and spatial reasoning Tong et al. (2024b); Qi et al. (2025); Yuksekgonul et al. (2022); Ma et al. (2023). Early approaches largely attribute these shortcomings to the visual encoder or the vision-language projector. In response, subsequent works have introduced stronger vision encoders Lu et al. (2024); Li et al. (2024) and more expressive projectors Liu et al. (2024a); Cha et al. (2024); McKinzie et al. (2024), aiming to supply the language model with richer and more comprehensive visual representations. Fu et al. (2025) suggests that this limitation reflects a failure of the LLMs to effectively utilize available visual information, rather than the quality of the visual information itself.

In this paper, we first revisit the conventional training paradigm of visual instruction tuning. Existing MLLMs are predominantly fine-tuned with a language-modeling objective, updating both the LLM and the vision-language projector while concentrating supervision almost entirely on textual outputs Li et al. (2024); Bai et al. (2023b); Chen et al. (2024c). As a result, visual tokens receive only indirect, language-mediated supervision despite comprising a substantial fraction of the multimodal input. In effect, the visual pathway remains under-supervised, raising a central question: *Is the prevailing multimodal training setup adequate for capturing and preserving visual information?*

We hypothesize that text-only supervision encourages the model to retain only those visual details that immediately aid text prediction, discarding other potentially useful cues. For instance, as in examples shown in Fig. 1, a caption such as *"A photo of a group of people holding a large flag."* provides little incentive to preserve the flag's color, the exact number of people, or their spatial layout—attributes needed for fine-grained image understanding. In short, text-only supervision aligns visual features with language efficiently, but does so at the cost of losing the richer and more structured representations provided by the vision encoder Venhoff et al. (2025); Neo et al. (2024).

To validate this hypothesis, we conduct an experiment (see Fig. 2) and observe that visual representations trained under exclusive textual supervision rapidly diverge from those produced by the input vision encoder, which we refer to as *visual representation misalignment*. Notably, we observe that enforcing alignment with the model's own vision encoder already yields substantial gains in fine-grained visual understanding, indicating that MLLMs discard visual information during training.

Motivated by these findings, we propose **VIsual Representation ALignment (VIRAL)**, a simple yet effective regularization strategy that directly supervises the visual pathway in MLLMs by aligning their internal visual representations to a reference vision model using a cosine-similarity–based loss. While the model's own vision encoder can serve as a minimal alignment reference, we further find that substantially larger gains are achieved when stronger vision foundation models (VFMs) Oquab et al. (2023); Kirillov et al. (2023); Yang et al. (2024); Ranzinger et al. (2024) are used instead. Trained with vision-centric objectives, VFMs act as a stronger alignment reference that not only prevents visual information loss, but also provides complementary visual knowledge absent from the model's own vision encoder. As a result, aligning MLLMs with VFMs enables more effective visual reasoning over complex inputs. Through extensive experiments on widely adopted multimodal benchmarks, we demonstrate that VIRAL consistently delivers significant improvements across all tasks. We summarize our contributions as follows:

- We show that, under the visual instruction tuning paradigm, internal visual representations in MLLMs often drift from those of their vision encoders, leading to degraded spatial reasoning due to the loss of fine-grained visual information.
- We propose **VIRAL**, a novel regularization strategy that explicitly aligns MLLM visual representations with pretrained VFM features, preventing the loss of fine-grained attributes and enabling richer visual understanding.
- We show consistent improvements of an average **9.4%** over the baseline on standard multimodal benchmarks, with extensive ablation studies and analysis to validate our design choices.

2 RELATED WORK

Visual information processing in MLLMs. Recent studies (Kaduri et al., 2025; Zhang et al., 2025b; Jiang et al., 2025; Kang et al., 2025a) have begun to analyze how visual information is processed and transformed inside MLLMs. Prior work reveals a structured hierarchy in MLLMs, where early layers encode global visual context, intermediate layers capture fine-grained spatial information, and later layers integrate multimodal signals for generation (Kaduri et al., 2025; Zhang et al., 2025b). Within this hierarchy, the intermediate layers have been shown to play a critical role in visual grounding and spatial reasoning. Complementary to these structural analyses, recent work has highlighted limitations in how MLLMs utilize visual representations internally. Fu et al. (2025) show that even when high-quality visual representations are available within the model, the language model often fails to effectively exploit them for vision-centric tasks. Consistent with these observations, our analysis shows that fine-grained visual information is progressively lost during training, and that preserving such information in the intermediate layers—where spatial semantics emerge—is particularly important for vision-centric reasoning.

Improving visual information in MLLMs. While recent works have increasingly examined the internal information flow of MLLMs, most prior efforts remain concentrated on the input stage—particularly the use of frozen vision encoders. Improvements at this stage have largely focused on adopting stronger or multiple vision encoders (Kar et al., 2024; Lu et al., 2024; Shi et al., 2024; Azadani et al., 2025) or enhancing efficiency by reducing the overhead of visual tokens (Vasu et al., 2025; Yang et al., 2025; Wen et al., 2025). These advances have proven valuable, yet they primarily address the quality and efficiency of the initial visual representations, with comparatively less attention given to how visual information is processed and lost once injected into the model.

Representation supervisions. Representation-level supervision has recently gained attention in generative modeling. Methods such as REPA Yu et al. (2024) align internal representations with those of strong vision encoders to improve learnability during training Labs (2025). In MLLMs, several recent works Wang et al. (2024); Jain et al. (2025) similarly explore representation supervision to enhance visual perception. However, these methods simply utilize representations from VFMs to aid MLLMs to better solve downstream tasks such as providing geometric foundation features for better geometry understandings Jain et al. (2025). On the other hand, our work is motivated by analyzing why current MLLMs fail in fine-grained image understanding, where we identify a key problem of visual information loss and introduce representation alignment as an auxiliary task to prevent such visual information loss for improved capabilities in downstream vision-centric tasks.

3 PRELIMINARIES

Multimodal large language models (MLLMs). MLLMs typically consist of a pre-trained language model $LM_\theta(\cdot)$ and a vision encoder $V_\psi(\cdot)$, which is connected with a vision-language projector $P_\phi(\cdot)$, where θ, ψ, and ϕ denote corresponding learnable parameters. To generate answers grounded on both input image and text, the frozen vision encoder $V_\psi(\cdot)$ first extracts patch-level features from an input image $I \in \mathbb{R}^{H\times W\times 3}$ with height H and width W such that $\mathbf{z} = V_\psi(I) \in \mathbb{R}^{N\times D_{\mathbf{z}}}$, where N and $D_{\mathbf{z}}$ denote the number of visual tokens and the dimension of the visual features, respectively. In typical MLLMs, a linear vision–language projector $P_\phi(\cdot)$ maps these features into the language model's embedding space, producing a sequence of visual tokens $\mathbf{e}^{\text{img}} = P_\phi(\mathbf{z}) \in \mathbb{R}^{N\times D}$, where D is the hidden dimension of the language model. Text inputs are embedded into the h that $\mathbf{e}^{\text{text}} \in \mathbb{R}^{K\times D}$, where K denotes the length of the text tokens. and the language model processes the concatenated multimodal sequence.

During training, MLLMs are typically optimized using a text-only language modeling objective, where supervision is applied solely to the output text tokens:

$$\mathcal{L}_{\text{LM}} = -\frac{1}{K}\sum_{i=1}^{K} \log p_{\theta,\phi}(\mathbf{e}_i^{\text{text}} \mid \mathbf{e}_{<i}^{\text{text}}, \mathbf{e}^{\text{img}}). \tag{1}$$

As a result, visual representations $\mathbf{e}^{\text{img}}$ receive no explicit vision-specific supervision, and all learning signals are mediated through language prediction.

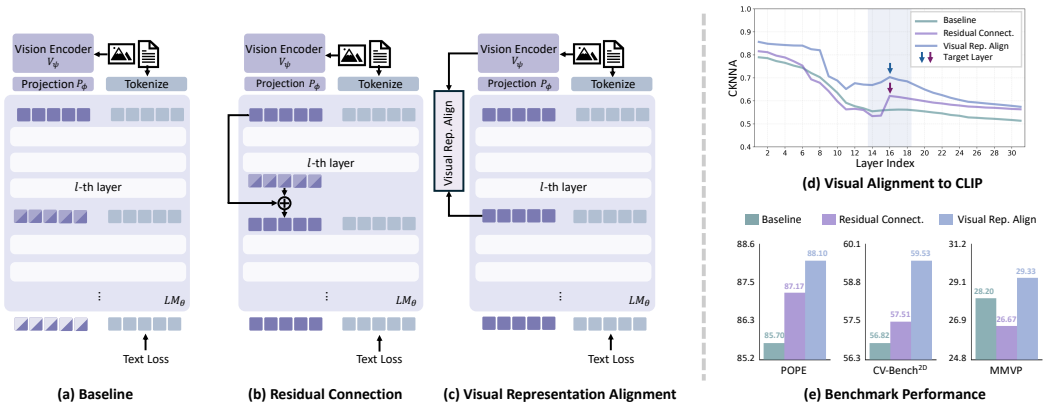

Figure 2: **Re-injecting or aligning visual features improves representation alignment and performance:** (a–c) Comparison of (a) baseline visual instruction tuning (Liu et al., 2023), (b) re-injecting visual features, and (c) visual representation alignment, all applied at the 16th layer. (d) Layer-wise alignment between visual tokens in MLLMs and vision encoder features, measured by CKNNA (Huh et al., 2024), with shaded regions denoting middle layers that are particularly important for visual understanding. (e) Benchmark performance corresponding to (a–c).

4 METHODOLOGY

4.1 DO MLLMS LOSE VISUAL INFORMATION?

While MLLMs take a substantial number of visual tokens as input, they are typically trained with a text-only language modeling loss applied to the output text tokens. Consequently, all learning signals are mediated through language supervision, and the visual representations $\mathbf{e}^{\text{img}}$ receive no vision-specific supervision, as illustrated in Fig. 2-(a). In the absence of explicit visual supervision, we hypothesize that the model learns to prioritize only those visual features that immediately aid textual prediction, often discarding other potentially useful information. This, in turn, causes the internal visual representations to drift away from the rich features produced by the vision encoder—an effect that can undermine performance on tasks requiring complex visual reasoning or grounding.

To empirically validate this hypothesis, we measure the similarity between the internal visual representations of LLaVA (Liu et al., 2024a) and the original visual features $\mathbf{z}$ extracted by its vision encoder (e.g., CLIP (Radford et al., 2021)). We adopt CKNNA (Huh et al., 2024) as a metric to quantify representational similarity.

As shown in Fig. 2-(d), similarity to CLIP features drops sharply after the early layers and remains low in deeper layers, indicating that the model's internal visual representations increasingly diverge from the encoder's input features. This trend suggests that, without explicit visual supervision, the model has little incentive to preserve the encoder's rich visual information.

Interestingly, despite the overall decline in alignment, the middle layers show a clear attenuation of this trend, with even a slight increase, suggesting that the network implicitly benefits from retaining visual representations at these layers when generating visually grounded answers. This observation aligns with prior analyses of information flow in MLLMs (Zhang et al., 2025b; Kaduri et al., 2025) and is also confirmed by our later layer-wise ablations, which show that visual information within the middle layers is most important for vision-centric tasks (see Sec. 5.3).

4.2 DOES PRESERVING VISUAL INFORMATION HELP?

Having observed the progressive visual information loss of the internal visual representations within MLLMs, we ask whether *explicitly preserving* such visual information is beneficial. Let $\mathbf{e}_\ell^{\text{img}} \in \mathbb{R}^{N\times D}$ denote the visual representations at the ℓ-th layer of MLLMs. As a direct approach (Fig. 2-(b)), we re-inject the projected visual representation $P_\phi(\mathbf{z})$ into an intermediate layer of the language model via a residual path:

$$\mathbf{e}_{\ell,i}^{\text{img}} \leftarrow \mathbf{e}_{\ell,i}^{\text{img}} + P_\phi(\mathbf{z}_i). \tag{2}$$

To isolate the effect of visual information retention without introducing new supervision, the model is trained solely with the original text loss $\mathcal{L}_{\text{LM}}$. Unless otherwise stated, we set $\ell = 16$ in a 32-layer model LLaVA (Liu et al., 2024a), as fine-grained visual understanding emerges most prominently in middle layers, consistent with later layer-wise ablations (see Sec. 5.3).

As shown in Fig. 2-(d), adding the residual connection better preserves the alignment with the encoder's visual features, as indicated by higher CKNNA similarity. Evaluated across standard benchmarks (Fig. 2-(e)), this approach shows general improvements over the baseline, supporting the hypothesis that retaining encoder-aligned visual information benefits downstream tasks. However, concerns remain that the residual connection often only provides *local impact* on the specific layer of injection rather than boosting the *entire* visual pathway of the MLLMs to better preserve the rich visual information originally provided by the input vision encoder.

4.3 Visual Representation Alignment

Representation alignment with encoder features. Beyond residual connection, we further explore a more principled approach, which is introducing an *explicit* regularization to align intermediate visual representations with the encoder features as an additional supervision signal; see Fig. 2-(c). Let $\mathbf{z}$ denote the frozen encoder features from $V_\psi(\cdot)$ and $\mathbf{e}_\ell^{\text{img}} \in \mathbb{R}^{N\times D}$ the visual representations at the ℓ-th layer of the MLLM. We introduce a learnable projection $P_\pi(\cdot)$ to map $\mathbf{e}_\ell^{\text{img}}$ into the encoder feature space and define the visual representation alignment loss:

$$\mathcal{L}_{\text{VRA}}(\mathbf{e}_\ell^{\text{img}}, \mathbf{z}) = -\frac{1}{N}\sum_{i=1}^{N} \text{sim}\Big(P_\pi(\mathbf{e}_{\ell,i}^{\text{img}}),\, \mathbf{z}_i\Big)\,, \tag{3}$$

where $\text{sim}(\cdot,\cdot)$ is cosine similarity and gradients do not flow into $\mathbf{z}$. Finally, we augment the language modeling loss with this alignment term, with λ controlling the strength of alignment:

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{LM}} + \lambda\,\mathcal{L}_{\text{VRA}}. \tag{4}$$

As shown in Fig. 2-(d,e), this alignment outperforms residual connection in both CKNNA similarity and multimodal benchmarks. Further analysis on this finding is provided in Appx. B. This shows that constraining intermediate features through an alignment loss offers stronger preservation of fine-grained semantics through explicit regularization, while residual connections offers only weak constraints without enforcing consistency at the feature level.

Despite the general performance boost from retaining encoder-aligned visual information, either by re-injecting projected features or applying visual representation alignment, a notable exception is MMVP (Tong et al., 2024b), which targets cases where CLIP-like features underperform. In this setting, performance shows only marginal improvement or even a slight drop, suggesting that propagating the encoder's features can also transmit its inductive biases and limitations. These findings raise the question of the *alignment target*: should the model remain tied to the original encoder features $\mathbf{z}$, or be guided toward more informative visual semantics? While aligning to $\mathbf{z}$ helps retain meaningful attributes, its utility is constrained by the encoder's representational capacity.

From encoder features to other VFMs. Motivated by this, we adopt stronger vision foundation models (VFMs) as teachers to supervise internal visual representations, providing richer vision-centric targets that complement language supervision. Building on this insight, we propose **VIsual Representation ALignment (VIRAL)**, which aligns intermediate MLLM visual representations with features from a pretrained VFM, thereby preserving richer visual semantics than those available from the encoder alone. Let $\mathcal{E}(\cdot)$ denote a pretrained VFM encoder. Given an input image I, the encoder produces target features $\mathbf{y} = \mathcal{E}(I) \in \mathbb{R}^{N\times d}$, where d is the VFM feature dimension. Let $\mathbf{e}_\ell^{\text{img}} \in \mathbb{R}^{N\times D}$ be the MLLM's visual representations at layer ℓ, and let $P_\pi(\cdot)$ be a learnable projection that maps $\mathbf{e}_\ell^{\text{img}}$ into the VFM feature space. We instantiate the

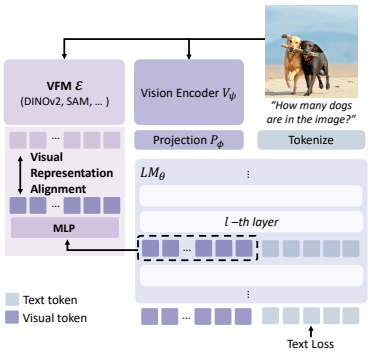

Figure 3: **Illustration of VIRAL.**

Language Model	Vision Encoder	$\mathcal{L}_{\text{VRA}}$	CV-Bench$^{\text{2D}}$	MMVP	What's Up	Hallu. Bench	POPE	MMStar	MME	MMMU	MMBench^{En}	MMVet	AI2D	OCRBench
Vicuna-1.5-7B	CLIP	✗	56.82	28.20	40.13	44.48	85.70	**33.93**	1650.21	33.78	**63.23**	26.65	53.82	**319.0**
		✓	**59.67**	**33.33**	**48.55**	**46.06**	**88.32**	**33.93**	**1694.52**	**35.33**	63.06	**29.45**	**54.37**	315.0
	SigLIPv2	✗	58.90	28.22	40.90	44.69	90.13	36.53	1738.96	34.00	64.00	29.31	55.76	**384.0**
		✓	**62.66**	**33.11**	**44.40**	**45.95**	**90.77**	**37.20**	**1835.62**	**37.66**	**64.18**	**30.41**	**56.15**	383.0
Qwen2.5-7B	CLIP	✗	58.97	33.47	59.08	44.37	**85.88**	39.20	1743.56	38.22	64.18	26.42	61.46	306.0
		✓	**60.50**	**36.07**	**63.57**	**45.01**	84.92	**39.67**	**1765.65**	**41.44**	**68.13**	**28.62**	**64.12**	**310.0**
Vicuna-1.5-13B	CLIP	✗	57.51	32.30	44.44	41.74	87.12	34.47	1599.04	34.89	66.07	31.47	**57.67**	334.0
		✓	**58.97**	**37.80**	**62.26**	**42.06**	**87.79**	**37.00**	**1636.62**	**37.22**	**66.07**	**32.39**	56.44	**336.0**

Table 1: **Effects of visual representation alignment.** We compare models trained with and without $\mathcal{L}_{\text{VRA}}$ across various vision encoders and LLM backbones, evaluating them on both vision-centric and general multimodal benchmarks. Our simple regularization, $\mathcal{L}_{\text{VRA}}$, combined with DINOv2, consistently improves performance.

visual representation alignment loss by replacing the encoder target $\mathbf{z}$ in Eq. 3 with $\mathbf{y}$:

$$\mathcal{L}_{\text{VRA}}(\mathbf{e}_{\ell}^{\text{img}}, \mathbf{y}) = -\frac{1}{N}\sum_{i=1}^{N} \text{sim}\Big(P_{\pi}(\mathbf{e}_{\ell,i}^{\text{img}}),\, \mathbf{y}_i\Big)\,. \tag{5}$$

Minimizing $\mathcal{L}_{\text{VRA}}$ regularizes the MLLM's internal visual pathway to align with the VFM. The overall framework is illustrated in Fig. 3.

5 Experiments

5.1 Experimental Settings

Implementation details. We build on the widely used LLaVA-1.5 (Liu et al., 2024a), which provides fully open-source model weights and training data, enabling controlled and reproducible analysis. We used Vicuna-1.5 (Chiang et al., 2023) as the language model with a CLIP vision encoder (Radford et al., 2021). Following its instruction-tuning recipe, we adopt LoRA (Hu et al., 2022) for efficient adaptation as prior work reports that LLaVA-1.5 with LoRA attains comparable performance to full fine-tuning (Liu et al., 2024a). We use the original LLaVA-665K dataset without any additional data. The visual-representation projector $P_{\pi}(\cdot)$ is a lightweight three-layer MLP with SiLU activations, and we set $\mathcal{E}(\cdot)$ to DINOv2 as default (Sec. 5.3).

Evaluation. To demonstrate the effectiveness of VIRAL, we evaluate it on widely used benchmarks across four categories, which together assess whether our method improves vision-centric and hallucination-sensitive performance without compromising general MLLM capabilities: (1) vision-centric tasks requiring spatial reasoning or object counting, including CV-Bench$^{\text{2D}}$ (Tong et al., 2024a), What's Up (Chen et al., 2025; Kamath et al., 2023), and MMVP (Tong et al., 2024b); (2) multimodal hallucination detection, using POPE (Li et al., 2023) and Hallusionbench Guan et al. (2024); (3) general multimodal understanding, including MME (Yin et al., 2024), MMStar (Chen et al., 2024a), MMMU Yue et al. (2024), MMBench Liu et al. (2024c), MMVet Yu et al. (2023), as well as (4) document understanding benchmarks such as AI2D Kembhavi et al. (2016), and OCR-Bench Fu et al. (2024). We adopt lmms-eval Zhang et al. (2024) when available, and otherwise follow the original benchmark protocols. Detailed implementation details are provided in Appx. A.

5.2 Main Results

Tab. 1 summarizes results on vision-centric, hallucination, general vision–language benchmarks and document understanding benchmarks.

LLaVA-1.5-7B. With identical training settings, VIRAL consistently outperforms the baseline, yielding substantial improvements on fine-grained vision-centric tasks while preserving general multimodal performance, including document understanding, via intermediate feature alignment with VFM targets.

With stronger vision encoders. To demonstrate that our method goes beyond simply adopting a stronger vision encoder or input features, we evaluate our method using an architecture

Table 2: **Ablation study on key design components.** We analyze the effects of (i) different vision foundation models (VFMs) and (ii) alignment target layers, through evaluation on vision-centric and general multimodal benchmarks. All experiments are conducted on the LLaVA-1.5-7B baseline.

VFM	Layer Index	CV-Bench^{2D}	MMVP	What's Up	POPE	MME
Baseline		56.82%	28.20%	40.13%	85.70%	1650.21
Ablation studies on different VFMs						
DINOv2	16	**59.67%**	**33.33%**	48.55%	88.32%	**1694.52**
CLIP	16	59.53%	29.33%	44.50%	88.10%	1548.49
SAM	16	57.58%	30.27%	**49.84%**	88.34%	1648.77
DAv2	16	58.55%	28.67%	47.29%	**88.70%**	1682.42
RADIO	16	57.59%	31.80%	47.35%	88.52%	1692.94
Ablation studies on different target layers						
DINOv2	4	58.55	30.67	45.05	87.68	1720.36
DINOv2	8	58.28	27.70	48.32	88.43	1662.67
DINOv2	12	57.77	28.59	48.19	88.27	1648.88
DINOv2	16	**59.67**	**33.33**	**48.55**	88.32	1694.52
DINOv2	20	55.22	27.41	48.04	88.39	1705.97
DINOv2	24	55.77	27.48	47.99	88.10	1740.55
DINOv2	28	54.87	27.19	47.82	**88.56**	**1755.86**
DINOv2	32	56.12	26.52	47.60	87.32	1678.69

equipped with SigLIPv2 (Tschannen et al., 2025), trained with both contrastive (CLIP-style) and self-supervised (DINO-style) objectives. Even with this stronger encoder, our alignment loss yields consistent improvements, showing that the gains stem from the alignment itself.

Robustness to language backbones We additionally evaluate a scaled-up language backbone, comparing Vicuna-1.5-13B with its 7B counterpart, as well as Qwen2.5-7B (Bai et al., 2025), to demonstrate that our method is not tied to a specific language model. Taken together, these results indicate that regularizing intermediate visual representations is a generally applicable strategy that improves MLLMs across vision encoders, model scales, and language backbones.

5.3 Component-wise Analysis

In this ablation study, we conduct a comprehensive analysis of key design choices underlying our framework, focusing on core components: the selection of target visual features and the choice of alignment layer. We evaluate the impact of each component across five benchmarks (CV-Bench, MMVP, What's Up, POPE, and MME) to validate their respective contributions to the model's performance on vision-grounded tasks. Additional ablation studies on alignment objectives and target layers are provided in Appx. C and Appx. D.

Vision foundation models. We begin by identifying the most effective target visual features for enhancing the alignment of internal visual representations within MLLMs. While residual connections and alignment with CLIP (LLaVA-1.5's original vision encoder) help improve visual comprehension (Fig. 2), their performance on spatial tasks like MMVP is limited—likely due to CLIP's weakness in modeling spatial relations (Yuksekgonul et al., 2022). To address this, we evaluate several stronger vision foundation models (VFMs), including DINOv2 (Oquab et al., 2023), CLIP (Radford et al., 2021), Segment Anything (Kirillov et al., 2023) (SAM), Depth Anything v2 (Yang et al., 2024) (DAv2), and RADIOv2.5 (Heinrich et al., 2025). As shown in Tab. 2, our analysis confirms that aligning with stronger visual features indeed enhances visual understanding, with DINOv2 and other VFMs demonstrating improved performance compared to CLIP. Results show that DINOv2 consistently emerges as the most effective and versatile, and we thus adopt DINOv2 as the default visual foundation model for all experiments.

Target layers. We then analyze alignment at individual target layers to determine the most effective position. As shown in the *target-layers* ablation results in Tab. 2, we report performance at every 4th layer throughout the network. We observe that performance varies depending on the alignment layer, with the 16th layer of the 32-layer model consistently yielding stronger results across multiple benchmarks. This trend is consistent with prior findings (Zhang et al., 2025b; Kaduri et al., 2025) and our earlier analysis, suggesting that certain intermediate layers in MLLMs are particularly attuned to visual information processing.

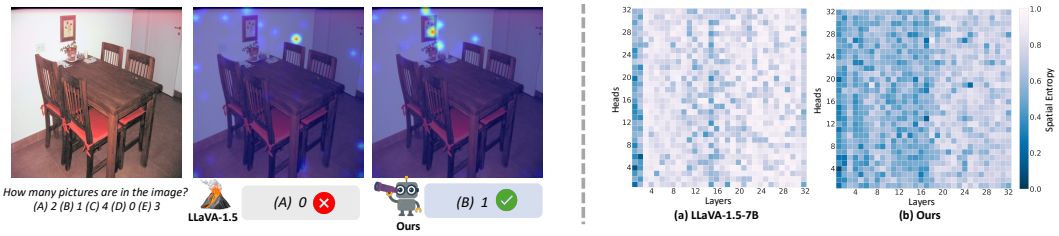

Figure 4: **Analysis of attention.** Qualitative comparison on text-to-image attention maps (left) and quantified spatial entropy of attention across layers and heads (right).

5.4 Attention Analysis

We analyze the effectiveness of our proposed framework with visual representation alignment in terms of text-to-image attention, as shown in Fig. 4 (left). The attention map produced by the $\mathcal{L}_{\text{VRA}}$ trained model exhibits more semantically aligned focus on image regions corresponding to the given textual prompts. To quantify this, we adopt spatial entropy (Batty, 1974), motivated by (Kang et al., 2025b), as a metric of attention localization. As shown in Fig. 4 (right), LLaVA-1.5-7B exhibits high entropy across layers and heads, reflecting dispersed attention patterns, whereas our model shows consistently lower entropy—particularly at the aligned intermediate layer—indicating more selective and meaningful attention patterns.

5.5 Qualitative Analysis

We qualitatively demonstrate the effectiveness of our proposed approach through detailed analyses of model outputs and internal visual representations. By adopting VIRAL, we observe substantial improvements in performance on vision-centric tasks such as instance counting and understanding spatial relationships. As illustrated in Fig. 5, VIRAL correctly answers challenging visual questions related to the number of objects and spatial positioning, whereas the baseline model, LLaVA-1.5-7B, frequently fails.

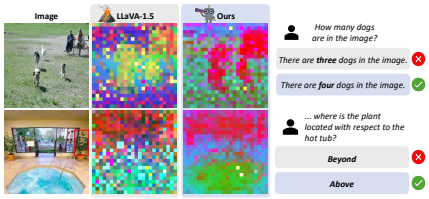

Figure 5: **Qualitative comparison of baseline and VIRAL.** The first column shows the input image–question pairs, and the next two present LLaVA-1.5 and VIRAL results with PCA visualizations and answers. VIRAL yields structured embeddings and correct answers on counting and spatial tasks where the baseline fails.

Furthermore, by aligning internal visual representations with robust vision foundation models (VFMs), the semantic quality of intermediate representations is significantly enhanced. This improvement is clearly evidenced in the PCA visualizations shown in Fig. 5. We apply PCA to the visual representations obtained from the 16-th layer of Ours and LLaVA-1.5-7B, where our method yields more structured and semantically coherent embeddings compared to the baseline. These visualizations highlight that our alignment strategy effectively guides the model to preserve critical visual details, thereby facilitating better fine-grained visual comprehension. Additional visualizations are provided in Appx. G.1 and G.2.

5.6 Training Efficiency

To further showcase the additional benefits of VIRAL, we evaluate vision-centric benchmarks, including CV-Bench^{2D} and MMVP, averaging accuracy at every 1K training step over the 5.2K training steps of the visual instruction tuning stage (Fig. 6). Both CLIP-based models trained with VIRALconverge faster and surpass baseline performance within 3K steps. Since our method introduces only about a 3% overhead in total training time, these earlier performance gains can translate into im-

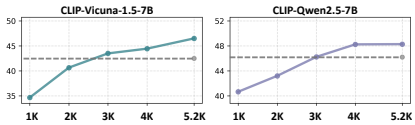

Figure 6: **Training Efficiency.** Performance with $\mathcal{L}_{\text{VRA}}$ (solid) evaluated every 1K steps, averaging accuracies on CV-Bench^{2D} and MMVP. Models trained with $\mathcal{L}_{\text{VRA}}$ achieve faster convergence. Dashed lines represent converged performance of baseline.

proved scalability. This indicates that our approach enhances final accuracy while also accelerating training.

6 Conclusion

In this work, we propose VIRAL, a simple yet effective regularization strategy that aligns the internal visual representations of MLLMs with those from pre-trained vision foundation models. Our approach helps preserve fine-grained visual semantics often discarded under text-only supervision, thereby enabling more accurate spatial reasoning and object grounding.

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APPENDIX

A ADDITIONAL IMPLEMENTATION DETAILS

All experiments in this paper are conducted on four NVIDIA A100 GPUs (40 GB each).

Vision foundation models. We use a diverse set of pretrained VFMs to supervise internal visual representations. DINOv2 (Oquab et al., 2023), CLIP (Radford et al., 2021), and Depth Anything v2 (Yang et al., 2024) (DAv2) are used as patch size 14 models, while RADIO-v2.5 (Heinrich et al., 2025) and SAM (Kirillov et al., 2023) are used as patch size 16 models. To match the 576 visual tokens produced by CLIP-ViT-L/14 at 336×336 resolution in LLaVA-1.5 (Liu et al., 2024a), we adopt the same resolution for patch size 14 models and resize inputs to 384×384 for patch size 16 models. For SAM, which expects 1024×1024 inputs, we pad the interpolated features to 1024×1024 and crop them to the region corresponding to the original image, following AM-RADIO (Ranzinger et al., 2024) to avoid quality degradation.

The cosine similarity $\mathrm{sim}(\mathbf{x}, \mathbf{y})$, as done in previous works, is computed as following $\mathrm{sim}(\mathbf{x}, \mathbf{y}) = \frac{\mathbf{x}^\top \mathbf{y}}{\|\mathbf{x}\|_2 \|\mathbf{y}\|_2}$. To balance the alignment loss $\mathcal{L}_{\mathrm{VRA}}$ with the language modeling loss $\mathcal{L}_{\mathrm{LM}}$, we set $\lambda = 0.5$ by default.

Benchmark settings. To demonstrate the effectiveness of VIRAL, we evaluate it on widely used benchmarks including CV-Bench, MMVP, What's Up, POPE, MME, and MM-Star. We only use the 2D subset of CV-Bench, as 3D tasks are beyond our scope. For simplicity, we report overall accuracy on CV-Bench$^{\mathrm{2D}}$ instead of separately averaging $\mathrm{ADE20K}$ and COCO. For MMVP, we follow its standard evaluation protocol using pair accuracy, but for stability, we report the average accuracy over 10 runs. For POPE, we evaluate on COCO following LLaVA and report the average accuracy across the "random" and "popular" subsets. For What's Up, we report the average accuracy between $\mathrm{COCO}_{\text{one}}$ and $\mathrm{COCO}_{\text{two}}$. For MME, we report MME^{EN} along with the sum of the perception and cognition categories, and for MM-Star, we follow their standard evaluation protocols.

Spatial entropy. For Fig. 4, we compute average spatial entropy over generated text tokens. We use question–answer pairs from (Zhang et al., 2025b), which augment GQA (Hudson & Manning, 2019) with diverse categories and constrain answers to a single word or phrase. Among these, we focus on the Relation category and report the average spatial entropy within this subset.

Robustness Analysis We investigate whether our representation alignment loss enables MLLMs to better capture spatial relationships. Prior work (Qi et al., 2025) shows that many MLLMs are weakly grounded in 2D spatial structure: even when visual tokens are randomly permuted—effectively destroying image layout (see Fig. 7)—performance drops only marginally, suggesting an order-insensitive, bag-of-patches representation. To assess whether our method increases sensitivity to spatial cues, we permute visual tokens $\mathbf{z} = V_\psi(I)$ before feeding them into $\mathrm{LM}_\theta(\cdot)$ and evaluate performance on the spatial reasoning category of CV-Bench$^{\mathrm{2D}}$. As shown in Tab. 3, while the text-only supervised baseline exhibits minimal degradation, our model suffers substantially larger drops, indicating stronger reliance on spatial structure. This confirms that our loss encourages MLLMs to exploit fine-grained spatial relationships rather than treating visual inputs as unordered tokens.

Table 3: **Robustness to token permutation.** Number of correct predictions out of 788 spatial reasoning tasks in CV-Bench$^{\mathrm{2D}}$.

Vision Enc.	$\mathcal{L}_{\mathrm{VRA}}$	original	patch shuffle	Δ
CLIP	✗	400	374	−26 (6.5%)
	✓	414	360	**−54 (13.0%)**
SigLIPv2	✗	374	353	−21 (5.6%)
	✓	436	353	**−83 (19.0%)**

Patch permutation. For our patch permutation experiment, we adopt the analysis pipeline originally proposed in (Qi et al., 2025). Specifically, we begin by extracting image features z from the vision encoder using $z = V_\psi(I)$, where I is the input image. Here, $z \in \mathbb{R}^{N \times H}$, with N denoting the number of visual tokens and H the dimensionality of the vision encoder features. Before processing the vision features z with the vision-language projector $P_\phi(\cdot)$ and language model $LM_\theta(\cdot)$, we apply a random permutation on the order of the visual tokens N, which is shown in the visualization of Fig. 7. This makes it extremely difficult to understand the visual attributes of the image, enabling

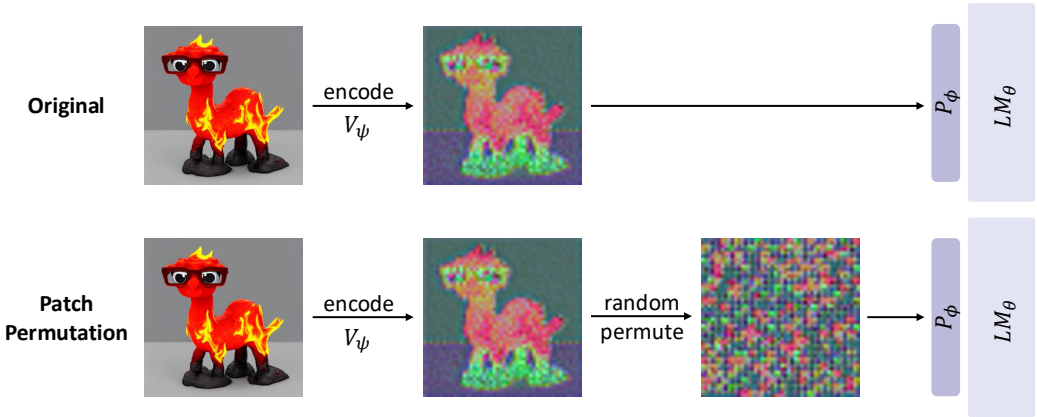

Figure 7: **Visualization of patch random permutation experiments.**

us to evaluate how much the MLLM was understanding and utilizing the visual attributes originally available in the image.

B EXTENDED EXPLORATION OF THE PILOT STUDY

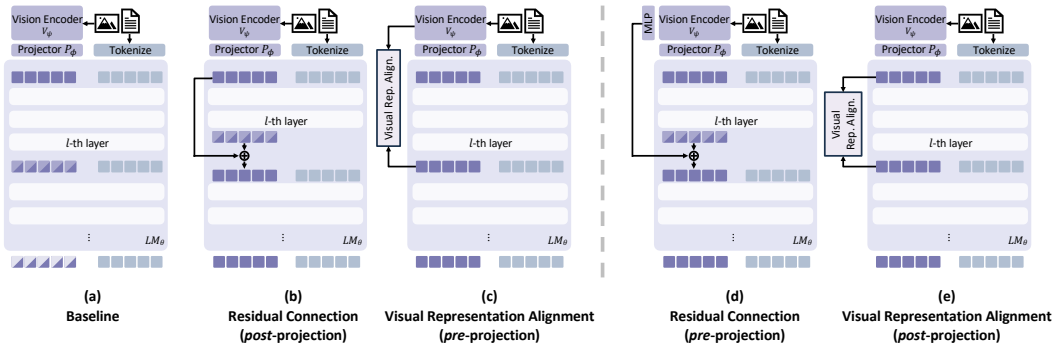

Figure 8: **Extended exploration of the pilot study.**

In Sec. 4, we demonstrated that MLLMs exhibit progressive visual information loss across layers, and that preserving such information can enhance their visual understanding (Fig. 8-(b,c)). In this section, we compare two additional strategies for preserving visual information: a residual connection with the raw encoder feature prior to projection (*pre*-projection) as a direct approach to feature re-injection (Fig. 8-(d)), and our proposed visual representation alignment with the projected features (*post*-projection) provided to the language model (Fig. 8-(e)).

Table 4: **Benchmark performance of the pilot study.**

	POPE	CV-Bench^{2D}	MMVP
Baseline	85.70%	56.82%	28.20%
(b)	87.17%	57.51%	26.67%
(c)	**88.10%**	**59.53%**	**29.33%**
(d)	85.47%	53.62%	19.33%
(e)	86.99%	57.23%	28.53%

Residual connection with *pre*-projection features. Our investigation leverages *pre*-projection features—raw encoder features $\mathbf{z}$ prior to the projector—through a direct residual connection to mitigate visual information loss within the language model, where a lightweight adapter $P_{\phi'}(\cdot)$ is

employed for dimensional compatibility. As illustrated in Fig. 8-(d), we conduct one such experiment that re-injects $\mathbf{z}_i$ into $\mathbf{e}_{\ell,i}^{\text{img}}$ such that

$$\mathbf{e}_{\ell,i}^{\text{img}} \leftarrow \mathbf{e}_{\ell,i}^{\text{img}} + P_{\phi'}(\mathbf{z}_i). \tag{6}$$

However, as shown in Tab. 4-(d), this approach generally performs worse than the baseline. This is because the raw encoder features, which have not passed through the pre-trained projector, are not sufficiently aligned with language features (Liu et al., 2023), and their direct residual connection consequently disrupts vision–language alignment in the intermediate layers. These findings suggest that incorporating external features into the internal visual pathway of LLMs requires more careful design.

Visual representation alignment with *post*-projection features. Next we further explore aligning the intermediate visual representation with the *post*-projection features, as shown in Fig. 8-(e). Here, we follow the same experimental setting as in Sec. 4.3, while $\mathcal{L}_{\text{VRA}}$ is defined as:

$$\mathcal{L}_{\text{VRA}} = -\frac{1}{N}\sum_{i=1}^{N} \text{sim}\Big(P_{\pi}(\mathbf{e}_{\ell,i}^{\text{img}}),\ P_{\phi}(\mathbf{z}_i)\Big). \tag{7}$$

The results presented in Tab. 4-(e) indicate that this approach generally improves performance over the baseline on vision-centric benchmarks, yet underperforms compared to leveraging raw features from the vision encoder. This may be attributed to the insufficient preservation of visual information in the *post*-projection features compared to the raw encoder outputs (Verma et al., 2024; Cha et al., 2024; Li et al., 2025).

C Additional ablation studies

Table 5: **Ablation study on key design components.**

VFM	Ladyer Index	Objective	CV-Bench^{2D}	MMVP	What's Up	POPE	MME
Baseline			56.82%	28.20%	40.13%	85.70%	1650.21
Ablation studies on different multi-layer targets							
DINOv2	16	Cos. Sim.	**59.67%**	**33.33%**	48.55%	**88.32%**	**1694.52**
DINOv2	$15-17$	Cos. Sim.	59.32%	28.00%	47.17%	87.61%	1639.72
DINOv2	$14-18$	Cos. Sim.	49.62%	22.55%	42.58%	87.90%	1444.32
Ablation studies on different alignment objectives							
DINOv2	16	Cos. Sim.	**59.67%**	**33.33%**	48.55%	**88.32%**	**1694.52**
DINOv2	16	Relation	58.83%	26.60%	**49.05%**	87.58%	1674.30

Number of target layers. To investigate the effective number of target layers, we evaluate *multi-layer targets* around the 16th—specifically ±1 (15–17) and ±2 (14–18) ranges—and observe that applying alignment solely at the 16th layer achieves the best performance. These findings highlight that aligning visual representations at a specific pathway responsible for visual representation processing, rather than uniformly across multiple layers, is more effective in enhancing the visual understanding capabilities of MLLMs. Based on this observation, we adopt the 16th layer as the default alignment target with DINOv2.

Alignment objectives. We investigate the impact of different feature *alignment objectives* during instruction tuning. Specifically, we compare the performance of models trained with a feature relation alignment objective, as a substitute for the proposed direct visual representation alignment loss. Here, the alignment objective is defined as a mean squared error (MSE) loss between the self-similarity matrices of the VFM features and the transformed intermediate representations, which effectively distills the structural relationships among visual features following recent approaches (Zhang et al., 2025a; Bolya et al., 2025). As shown in Tab. 5, we find that simple cosine similarity-based alignment loss yields higher performance, and adopt it as our default strategy for alignment.

Layer	CV-Bench^{2D}	MMVP	What's Up	POPE	MME
Baseline	56.82	28.20	40.13	86.90	1650
4	58.55	30.67	45.05	87.68	1720
8	58.28	27.70	48.32	88.43	1663
12	57.77	28.59	48.19	88.27	1649
16	**59.67**	**33.33**	**48.55**	88.32	1695
20	55.22	27.41	48.04	88.39	1706
24	55.77	27.48	47.99	88.10	1741
28	54.87	27.19	47.82	**88.56**	**1756**
32	56.12	26.52	47.60	87.32	1679

(a) DINOv2

Layer	CV-Bench^{2D}	MMVP	What's Up	POPE	MME
Baseline	56.82	28.20	40.13	86.90	1650
4	52.99	26.00	46.18	87.78	1614
8	**57.58**	24.66	44.42	87.88	1710
12	54.87	26.00	45.99	88.39	1672
16	**57.58**	**30.27**	**49.84**	88.34	1665
20	54.24	26.00	47.39	**88.42**	1698
24	57.79	26.66	48.87	87.79	1706
28	57.16	24.00	45.66	88.35	1698
32	57.09	29.33	44.42	87.80	**1717**

(b) SAM

Table 6: **Layer selection ablation for different visual foundation models.** All results are preliminary.

D Exploring target layers across different VFMs

Tab. 6 presents the target-layer ablation results when applying the $\mathcal{L}_{\text{VRA}}$ with different VFMs, specifically DINOv2 and SAM. As shown in Tab. 2 we demonstrate that visual representation alignment not only with DINOv2 but also with alternative VFMs consistently outperforms the baseline, indicating that our approach is not restricted to a specific visual foundation model and can flexibly leverage diverse VFM features. In Tab. 2 and 5, we further show that selectively applying the $\mathcal{L}_{\text{VRA}}$ to specific LLM layers is crucial for achieving effective alignment. Building on these findings, here we explore how the choice of the target layer can be specified across different VFMs, using DINOv2 and SAM as a representative examples. Across VFMs, we observe similar trends in target-layer selection. In particular, the layer ablation results on SAM also show that applying $\mathcal{L}_{\text{VRA}}$ to middle layers generally leads to larger performance improvements. This suggests that, even with a broader choice of target VFMs, aligning visual representations at intermediate LLM layers, where visual information is more actively processed, can be effective.

E Comparison with other training objectives

Table 7: **Comparison with reconstructive objective.**

Language Model	Vision Encoder	Objective	CV-Bench^{2D}	MMVP	What's Up	POPE	MMStar	MME
Vicuna-1.5-7B	CLIP	Baseline	56.82%	28.20%	40.13%	85.70%	33.93%	1650.21
		ROSS (Default)	54.24%	29.73%	43.57%	88.19%	**34.73%**	1648.87
		ROSS (Middle)	56.05%	31.40%	45.98%	88.21%	33.53%	1647.27
		VIRAL	**59.67%**	**33.33%**	**48.55%**	**88.32%**	33.93%	**1694.52**

We compare our method with ROSS (Wang et al., 2024), which applies a reconstructive objective to the final hidden state of the visual representations. To isolate the sources of improvement, we implement two variants under identical experimental conditions: ROSS (Default), reproducing the original method, and ROSS (Middle), which applies the same objective to an intermediate layer (16th layer as in our configuration for target supervision).

Tab. 7 reveals several key findings that validate our approach. First, the critical importance of intermediate layer supervision—a contribution of our work—is evidenced by ROSS (Middle) outperforming ROSS (Default), particularly on vision-centric benchmarks. Although both ROSS (Default) and ROSS (Middle) show improvements over the baseline which also shows the importance of providing supervision to the visual pathways, the superiority of ROSS (Middle) over ROSS (Defaults) confirms our hypothesis that supervising visual information flow at strategically chosen intermediate layers, rather than naively at the model's output, yields superior performance gains.

Second, and more fundamentally, our method significantly outperforms both ROSS variants across all benchmarks. This performance gap stems from a crucial distinction in objectives: while ROSS employs reconstruction-based objectives that excel at preserving low-level fidelity, such approaches are inherently less suited for capturing the higher-level semantic abstractions required by complex reasoning tasks (Zhang et al., 2023; Tong et al., 2024a). In contrast, our direct alignment with

pretrained vision foundation models provides richer semantic supervision that better bridges the vision-language gap.

These results demonstrate that our method's superiority arises from two synergistic contributions: (1) the strategic placement of supervision at critical intermediate layers, and (2) the use of semantically-rich alignment signals from vision foundation models rather than reconstruction-based objectives. Together, these design choices enable more effective visual representation learning for multimodal understanding.

F APPLICABILITY OF VIRAL TO OTHER MLLM ARCHITECTURES

Recent MLLMs employ various strategies to handle inputs with dynamic resolutions, including dynamically adjusting the sequence length of visual tokens (Bai et al., 2023b) or dividing high-resolution images into independently encoded tile grids (Liu et al., 2024b; Chen et al., 2024b). The latter approach preserves the original image resolution and is commonly adopted to capture fine-grained visual details.

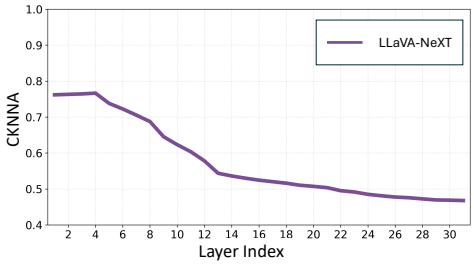

Figure 9: **Visual alignment of LLaVA-NeXT (Liu et al., 2024b).** Layer-wise alignment between visual tokens in MLLM and vision encoder features, measured by CKNNA and averaged across representations from tiled image splits.

To investigate whether VIRAL can be applied to such recent MLLM paradigms, we examine if our core motivation—mitigating vision information loss—remains relevant within this tiled image processing strategy. Fig. 9 demonstrates a decline in alignment scores between input visual features and layer-wise visual representations across the layers in LLaVA-NeXT (Liu et al., 2024b), as measured using CKNNA (Huh et al., 2024). This shows similar patterns observed in Fig. 2(d), suggesting that VIRAL can be applied orthogonally to such techniques and has the potential to similarly enhance fine-grained visual understanding in MLLMs designed for dynamic resolution handling.

G ADDITIONAL VISUALIZATIONS AND RESULTS

G.1 LAYER-WISE INTERNAL REPRESENTATIONS

We present PCA visualizations of the intermediate visual representations from all layers of LLaVA-1.5-7B and VIRAL in Fig. 10, enabling a layer-wise comparison of their representational structures. A qualitative comparison with the baseline reveals that visual representation alignment regularizes the MLLM's internal visual features, leading to more semantically coherent and structured representation, especially in the middle and later layers where meaningful vision understanding emerges.

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G.2 VISUAL REPRESENTATIONS WITH DIFFERENT VFMS

In addition to Fig. 5, we qualitatively present in Fig. 11 PCA visualizations of how internal visual representations evolve when aligned with different VFMs. Compared to the baseline representation from LLaVA-1.5-7B, VFM features exhibit more semantically structured organization. Aligning the MLLM's internal representations with these VFM features distills such structure, enabling the model to refer to enhanced and more coherent visual representations.

G.3 Attention map visualizations

In Fig. 12, we provide visualizations of text-to-image cross-attention maps in the MLLM to qualitatively support the attention analysis from the main paper. Compared to the baseline, the model trained with our method exhibits improved attention behavior by focusing more accurately and locally on regions relevant to the given multimodal context. This observation aligns well with the spatial entropy analysis in Fig. 4, where models trained with visual representation alignment show more focused and discriminative attention patterns.

H Use of Large Language Models

We disclose that Large Language Models were used to assist in grammar correction and polishing of the writing in this paper.

I Potential risk

We do not introduce any additional potential risk beyond those inherent to the underlying architectures, but the integration of LLMs and VLMs involves potential risks concerning data provenance, algorithmic bias, and stochastic hallucinations. These models remain susceptible to adversarial exploitation—specifically prompt injection and input perturbations—which may circumvent safety alignment to generate erroneous or prejudicial outputs.

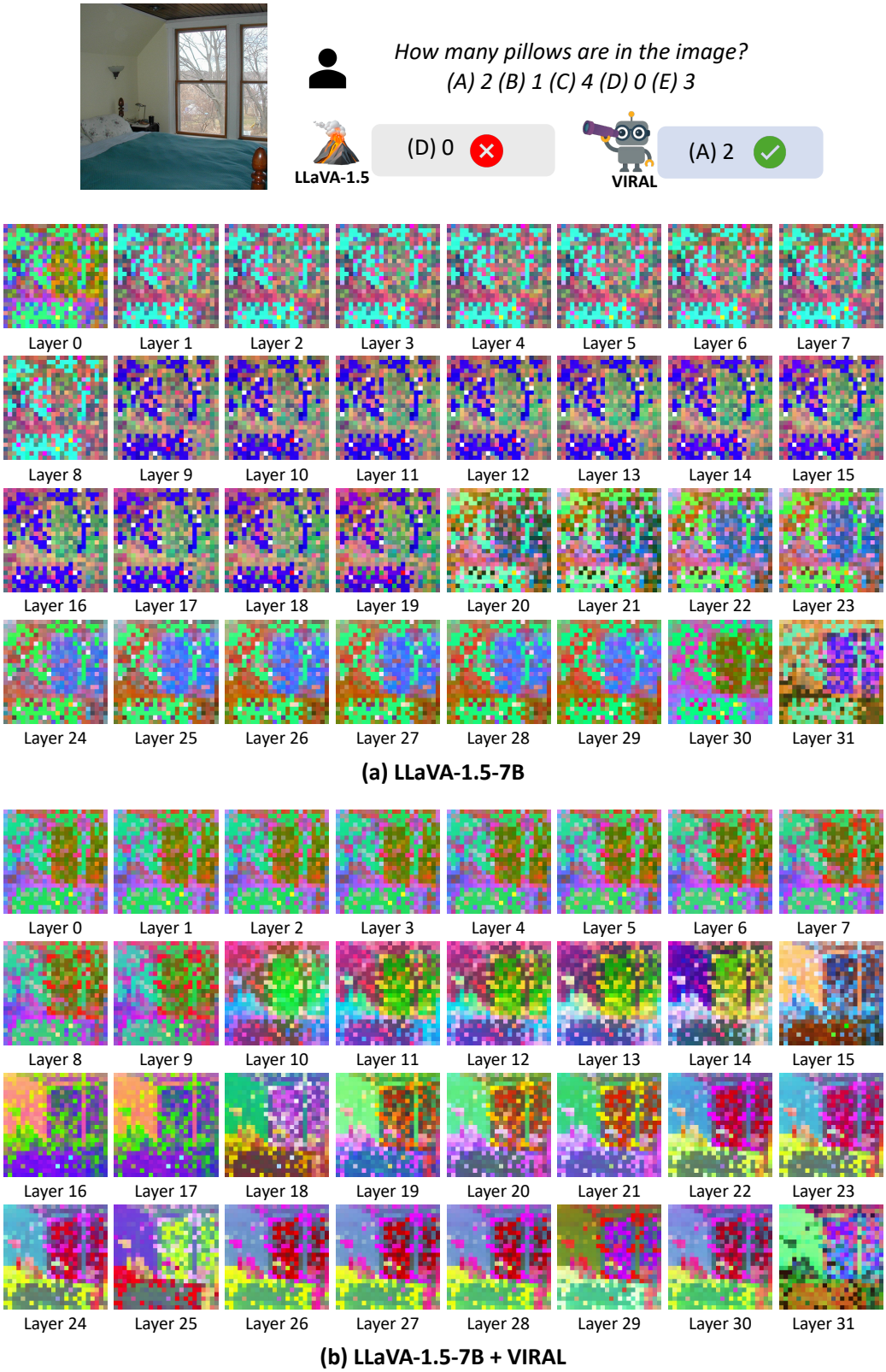

Figure 10: **Layer-wise PCA visualizations of visual representations** from (a) LLaVA-1.5-7B and (b) VIRAL (Ours).

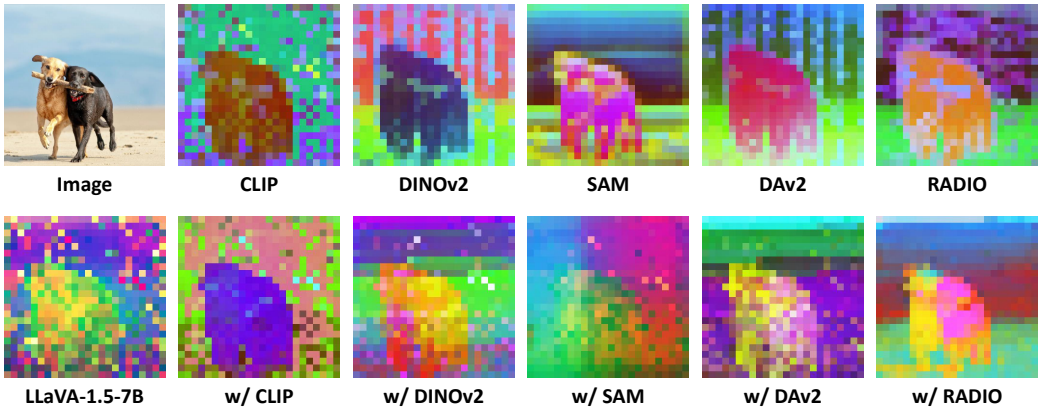

Figure 11: **PCA visualizations of 16th layer visual representations** aligned with different VFMs: CLIP (Radford et al., 2021), DINOv2 (Oquab et al., 2023), SAM (Kirillov et al., 2023), DAv2 (Yang et al., 2024), and RADIO (Heinrich et al., 2025).

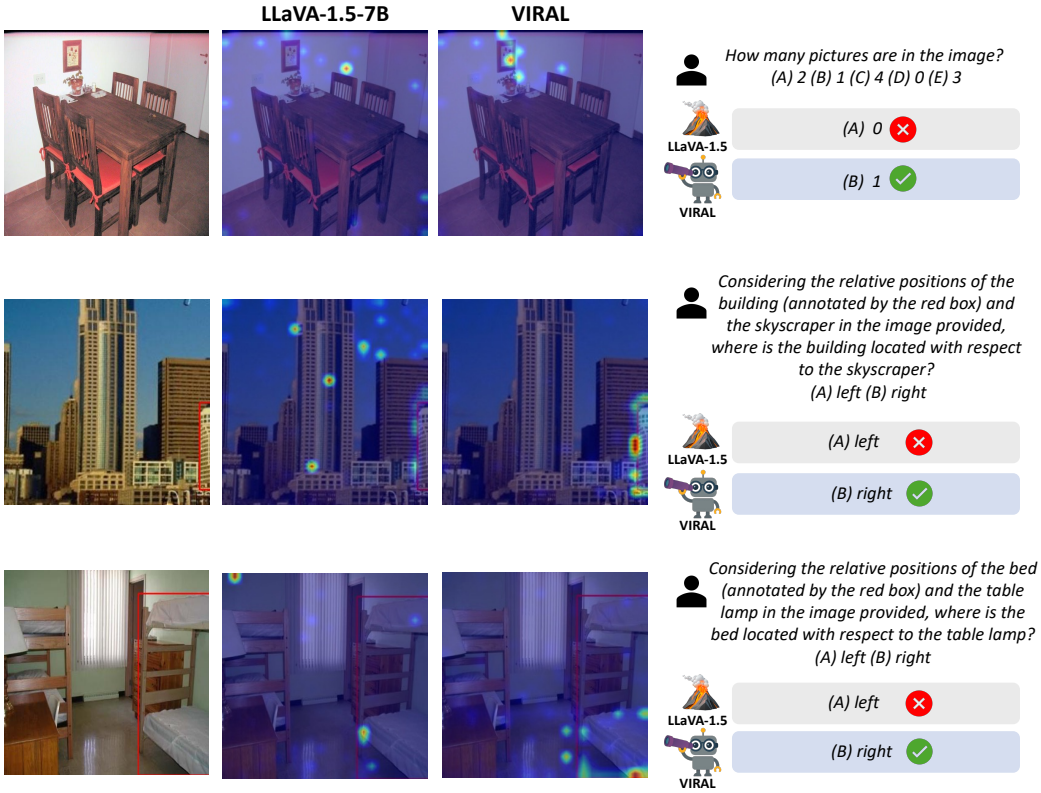

Figure 12: **Cross-attention map comparison for vision centric tasks.**